ABSTRACT

The two main activities of the Reactor Safety Division of the Institute for Radiological Protection and Nuclear Safety (IRSN/DSR) involve the technical support expertise for nuclear safety authorities and the research associated with this expertise mission. As regards its research activities, the IRSN has undertaken research and development actions in the field of non-destructive testing of materials in co-operation with laboratories of the Atomic Energy Commission (CEA).

At the outset of the industrialization process, this research work aims at solving the most difficult problems encountered in the course of inspections performed on the materials of nuclear installation components during in-service inspection. The purpose is first of all to demonstrate the capabilities of new inspection techniques based on the use of ultrasonic phased array transducers, or even eddy current flexible probes, for a better identification of defects in components difficult to inspect especially because of their complex shapes like small elbows or because of their coarse grain metallurgical structure. This research work which takes into account the shapes and the structure of components as well as defects and pays great attention to the case of real flaws aims also at simulating controls through mock-up experiments intended to validate simulation models. The contribution of this research work mostly related to ultrasonics and eddy currents and more recently to radiography simulation is presented and some examples are described.

INTRODUCTION

Maintenance operations in any nuclear installations include a large part of activities dedicated to non-destructive examination of materials. These mainly comprise surface inspection methods such as dye penetrant testing, magnetic particle testing and eddy current testing and volumetric examination methods such as radiography and ultrasonics.

Of these defect detection methods, the most frequently used on the safety-related components of nuclear installations involve the use of ultrasonic waves, which led IRSN to undertake research and development actions in this direction. For this purpose, it is working jointly with
external laboratories and in particular with the Atomic Energy Commission laboratories. Research is also under way in eddy current testing and radiography. Among the most stringent requirements that must be imposed on NDT methods, the essential are those that concern detection, sizing and identification of the shape of the defects, and allow us to determine whether a defect, is of planar character as in the case of crack or volumetric character.

If, for some of well identified cases, the inspection method allows us to easily achieve these objectives, in several cases it may be less reliable, in particular because of the particular shapes of the components (elbows, conical, or surface irregularities such as weld crown, the type of materials, or because a defect may be oriented in such a way as to make its detection and identification difficult, or because the defects are very narrow.

For these reasons, IRSN considers that it is essential to continue to make progress in the NDT field, both in order to specify the performances of the currently available methods (using simulation for example) and to develop new methods. It is for this reason that demonstration studies are being conducted by IRSN in order to develop ultrasonic probe and eddy current prototypes capable of better defect detection and better assessing their harmfulness related to their shape (planar crack, volumetric defects etc.). Of course, after the demonstration and basic concept validation studies, it will be up to the industrialist to carry on from there.

THE BENEFITS OF RESEARCH

The research into non-destructive testing methods conducted upstream the industrialization phase are mainly aimed at eventually providing more efficient means adaptable to most components and types of defect.

IRSN’s safety improvement objectives within the framework of this research are to :
- anticipate the risk of occurrence of new defects induced by the ageing of nuclear installations by initiating demonstrative or incentive developments upstream the industrialization phase, on the components that are the most difficult to inspect,
- participate in the development of NDT simulation and modeling means for nuclear installations, that cover a very wide spectrum of all sectors of industry so that these simulation means can be used in materials assessment with the aim of determining the limits of the methods used.

These studies contribute to intensifying the IRSN's materials assessment capabilities required to better understand new problems arising from the ageing of components. They also help improve our knowledge of the orientation and evolution of the new techniques in order to enhance the safety aspect.

THE MAIN RESEARCH THEMES

The main ultrasonic research actions concentrate in particular on the development of inspection methods based on phased array transducers or simulation methods technology. The following are examples of developments :
- the FAUST system (Focusing Adaptive UltraSonic Tomography), an ultrasonic system prototype to monitor the ultrasonic field of a phased array transducer (ref. 1),
- a smart contact transducer the main purpose of which is contact-based inspection of complex shaped components such as small elbows. It has a real-time self-adaptive function that matches the ultrasonic field to the shape of the component (ref. 2),
- a phased array ultrasonic transducer to inspect primary nozzles with complex shapes and coarse grain structure material in order to detect and measure planar defects (ref. 3),
- means of simulation and modeling inspection of parts with complex shapes, integrated into the CIVA software developed by CEA for several sectors of industry (nuclear industry, aeronautics, etc.).
IRSN participates mainly in simulating complex shaped components and coarse grain materials, and more recently in integrating real defects. Most of IRSN’s participation is dedicated to validating models and to defining validations protocols based on experiment (ref. 4),
- a prototype phased array transducer for the examination of concrete structures (ref. 5).

The developments underway in eddy current methods concern mainly:

- the development of flexible multi-element eddy current probes with a high signal-to-noise ratio, designed to examine complex shapes (for example detection of fine cracks in Inconel 600 structures affected by stress corrosion),
- simulation (ref. 6).

A FEW EXAMPLES OF RESEARCH

Inspection of complex shape parts using a smart contact transducer

In most cases, ultrasonic examinations conducted on nuclear installation components generally prove to have acceptable performances for detection, identification and sizing of defects and their performances are confirmed at the end of methods qualification.
In some rarer cases, the performances may not be achieved by conventional ultrasonic examination methods on complex shaped components (small elbows, small nozzles, etc.) or on components with surface irregularities caused by weld crown or repairs, as shown in Figure 1. The difficulties may also be aggravated by the presence of coarse grain materials.

![Figure 1 – Complex shaped components](image)
For these reasons, IRSN has undertaken demonstrative and incitive research aimed at developing a prototype smart contact transducer with the specific capability of adapting the transmitted acoustic beam to the shape of the component in real-time.

The operating principle of the smart contact transducer and the related multi-element control system for a 3-D configuration is shown in Figure 2. They comprise:

- For the transducer part:
  - an array of small piezoelectric elements arranged on a flexible surface,
  - an internal instrumentation adapted to the real-time measured distortion of the flexible piezoelectric surface and corresponding to the profile of the part,

- For the sensor’s multi-element control system:
  - the Multi 2000 system (ref. 7), many functions of which are the result of research work initiated by IRSN, to develop a prototype multi-element ultrasonic examination system (ref. 1), that is now industrialized and used in several sectors of industry (nuclear industry, aeronautical construction, tube manufacturing, etc.).

  This system ensures:
  - processing of profilometer measurement data for real-time application of delay laws adapted to each piezoelectric element of the array in order to produce an optimized beam,
  - inspection imaging.

![Figure 2 – The smart contact transducer principle](image)

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Correct operation of the 2D and 3D prototypes has been demonstrated. As shown in Figure 3, defect detection and sizing by this ultrasonic method become possible in areas where conventional ultrasonic examination is impossible. On the picture in Figure 3 b, tip diffraction detection and sizing of the planar defect are very well ensured, whereas when there are no delay laws (Figure 3 a) or when using a planar contact probe, no defect detection is possible.

Figure 3 - Inspection of tilted notches located below the planar and irregular parts of the complex profile mock-up using the flexible phased array. Specimen and defects geometry and B-SCAN images using static acquisition mode (a), adaptive mode (b).

The smart contact transducer is now in the industrialization phase. Figure 4 shows a concrete example of this new technique. In this illustration, it is being used to examine repaired pipes that have a highly irregular surface. This case of application studied by CEA for EPRI is described in ref. 8.
Simulation research to predict ultrasonic inspection performances

CEA is currently developing a software tool named CIVA that takes into account the simulation needs of NDTs specified by the various sectors of industry such as nuclear industry, aeronautics, metallurgy, etc. This simulation software integrates the ultrasonic and eddy current techniques and should soon also include radiographic techniques. IRSN wanted to use this simulation tool for its own needs in order to be able to assess the performances of examinations methods and to estimate insofar as possible their limits of use as support for the expert assessment it is currently carrying out for the Nuclear Safety Authorities.

These simulation developments mainly concern cases of application to nuclear installation components, for which validation on mock-ups are systematically performed. Two cases of the use of ultrasonic simulation studied and described in more detail in ref. 4) are presented. The first concerns simulation of examinations of complex shaped components. The second concerns simulation of ultrasonic examination of thick components such as reactor vessel shell rings and takes into account the tilt and skew effect of defects in the components.

Simulation of ultrasonic contact inspection of complex surface components

Ultrasonic contact examination of complex shaped components using standard transducers such as Krautkramer WB45 and WB60 that generate 45° or 60° transverse waves may cause serious degradation of performances in cases where coupling between the part and the probe is difficult. This may impair detection or cause serious distortion of the acoustic beam generated in the part, as shown in Figure 5.
Moreover, as shown in Figure 6, the shape of the inner face of certain components may present particularities that complicate defect detection and analysis. The examination performances can of course be determined on mock-ups with artificial defects, however this method rapidly becomes very costly. This led IRSN to undertake simulation studies to predict the examination performances for the most varied cases likely to occur. For this purpose, mock-ups containing artificial planar defects were manufactured in order to validate the simulation models.

The description of the examination (shape of the part; probe characteristics; description of the defects) is defined using the simulation software or CAD software. Thus, simulation can be used to produce images and predict the ultrasonic responses obtained on the defects (amplitude, detection of tip diffraction signals at the top of cracks). It takes account of:
- transducer-part coupling and the presence of a water gap,
- interaction of the beam with the defined defect,
- bottom geometry.

Figure 7 shows a simple case of inspection simulation using 45° transverse ultrasonic waves on a part with a complex outer profile and a planar inner profile, containing holes and electro-eroded notches.
Figure 7 - Simulation of complex surface mock-up inspection with WB45 probe

Comparison with experiment

The simulation results obtained are comparable to those obtained from experiments on mock-ups and the effects of the complex geometry are correctly predicted.

Simulation of ultrasonic inspection of thick components: assessment of the tilt and skew effect of defects

The second example of simulations performed, concerns inspection of thick components such as nuclear reactor vessel shell rings, performed with immersed focused transducers. Mock-ups representing the components concerned were produced and planar defects between 6 and 25 mm high were introduced into the outer skin, below the cladding and in the base material itself. Some of these artificial defects have a small ligament and are slightly disoriented so as to study the effect of disorientation on the detection and sizing performances. Figure 8 shows a diagram of a mock-up used.
Figure 8 - Example of mock-up for ultrasonic simulation in shell components

Figure 9 shows an example of simulation on this type of mock-up with the most frequent imaging produced to interpret the results. The figure shows both the results obtained from mock-up experimentation and those obtained by simulation. The defects used are planar defects penetrating through to the outer wall. They are perpendicular and disoriented by 10° (tilt angle) on a 250 mm mock-up. The comparison between experimentation and simulation in terms of echo amplitude prediction, including at the top of planar defects, is very good. This demonstrates that the examination simulation tool is capable of predicting the examination performances for defects of different heights, including disoriented defects.

Figure 9 - Simulated and experimental results for the inspection of a planar mock-up with different height vertical and tilted notches
Similar acquisitions and simulation were also performed on sections of piping in order to validate the models on small diameters (ref. 4).

**Research in the field of eddy currents testing**

**Development of a prototype flexible eddy currents probe**

The need for development and improvement has also been expressed in other fields than ultrasonics. These needs are generally brought to light by unfavorable operating experience observed internationally or in nuclear facilities of all categories. These needs are identified in the eddy current NDT fields, and as for the ultrasonic field they concentrate on:
- Examination of complex shaped parts of components where very small defects must be detected with a strong signal-to-noise ratio.
- Simulation, to estimate the operating limits of the probes, including on extremely narrow defects.

For the new eddy current probe technologies also developed to meet aeronautical industry needs, research is under way to develop new flexible technologies adaptable to the geometry of complex shaped components with very small curvature in thickness ranges of 4 to 6 mm. Examples of possible applications:
- Steam generator tubes expansion transition areas,
- Parts of Inconel 600 components or others affected by stress corrosion cracking,
- Parts of components affected by thermal fatigue-induced cracking in thickness ranges compatible with eddy current methods.

Prototypes of flexible probes have been tested on sections of 316L pipes representative of reactor residual heat removal pipes (RHR). These pipe sections have been subjected to heating cycles in order to create cracking and crazing induced by thermal fatigue. Defect opening occurs within a range from 200µ to 15-20µ. Figure 10 below is a photograph of the inner part of this section of piping showing its network of cracks along with the C-scan image obtained using eddy current examination of the cracked area during the inspection of the inner face. All major cracks show a very good signal-to-noise ratio. The crazing corresponding to relatively narrow cracks (around 20µ) also shows signal-to-noise good conditions.
Figure 10 – Sections of cracked piping and eddy current C-scan mapping obtained using a flexible probe

Figure 11 below shows one of these prototype demonstration probes.

Figure 11 – Prototype of a flexible eddy currents probe

Finally, among the various concrete cases of application of the demonstrative development, IRSN selected a real configuration corresponding to a case arising from international operating experience. This case shows cracks at a weld on a vessel bottom head penetration in the South Texas plant in the United States. This case, described in ref. 10, and extracted from the NRC ADAMS database, is illustrated in Figure 12.

The objective of this development is to demonstrate the technical feasibility of an eddy current examination, with a flexible probe prototype, on the surface of the weld whose shape varies constantly due to the presence of small curves, and hence to obtain a high signal-to-noise ratio capable of detecting the smallest cracks.
Figure 12 – Example of possible application of an eddy current probe on a flexible support
CONCLUSION AND PROSPECTS

Within the framework of the technical expert assessment performed by IRSN for the nuclear safety authorities, it is frequently noted that NDTs are not always suitable for detecting, sizing and identifying all defects likely to occur in materials, in particular complex shaped components, coarse grain components or complex shaped defects. Moreover, the materials of components which are difficult to examine may be affected by degradation phenomena due to ageing of nuclear installations.

This has led IRSN to undertake demonstrative and incitive studies aimed at developing new prototype probes adapted to these difficult cases, and also to contribute to the development of simulation models for specific examinations in the nuclear sector so as to produce simulation tools providing technical assessment assistance that will help in assessing the performances and limits of the methods concerned.

This upstream research, which has no ambition to replace research undertaken by the operators, enables among others to upkeep and enhance the institute expert assessment competences independently of the operator, by providing expert assessment assistance tools.

Finally, as concerns the ageing of nuclear installations, this demonstrative and incitive research should help to find solutions to the most difficult technical problems for which technological solutions will absolutely have to be proposed in the near future.
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